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Abstract: Potential interactions between objects affect response selection in action-related object pairs. The present paper aimed to examine whether this effect is conditional on the knowledge about object functionality, or whether action-related structures such as handles are sufficient. This issue was investigated by utilizing a paradigm established by Xu, Humphreys and Heinke (2015). They presented imperative central targets which overlapped with task-irrelevant object pairs and required speeded left/right responses to the targets. With this paradigm, Xu et al. (2015) have identified two stable effects of implied actions between objects on response selection: an inhibitory effect on responses aligned with the passive object (e.g. a bowl in a bowl-spoon pair) and an advantage associated with responses aligned with the active objects (e.g. a spoon). The present paper utilized these two effects as the indexes of response selection in paired-object scenarios, and found that active-passive object pairs without established functionality (e.g. a saw and a bowl, Experiment 1) generated the same effects, suggesting that response selection does not rely on functionality knowledge of given object pairs. Further, the two effects were also observed in passive-passive object pairs with handles (e.g. a cup-nail pair), but not in those without a handle (e.g. a bowl-nail pair, Experiment 2), and remained when the active objects were replaced by novel objects with handle but no known functionality (Experiment 3), suggesting that the action-related structures of objects are sufficient to affect response selection. The present study empirically illustrated the automaticity and directness of the extraction of potential interaction between objects, probably based on the relative location of action-related structure of objects.

Keywords: stimulus-response compatibility effect, paired objects, implied actions, action possibility, affordance

1 Introduction

Gibson (1979) postulated in his influential ecological approach of vision that humans directly detect action possibilities (affordances) from the environment and determine actions towards objects. However, current theories such as the two visual stream theory (Goodale & Milner, 1992; Milner & Goodale, 2006; Milner & Goodale, 2008) and the dual route model of object action and naming (Riddoch, Humphreys, & Price, 1989; Yoon, Heinke, & Humphreys, 2002) suggest that parallel routes exists in object perception, and actions towards objects can be determined via both routes. In the spirit of Gibson's affordance theory, the direct route mainly extracts possible actions based on object shape and structures (e.g. the handle-shaped parts; for emparical evidence see Buccino, Sato, Cattaneo, Rodà, & Riggio, 2009; Wulff & Humphreys, 2015) while the indirect route involves the retrieval of semantic and functional knowledge of objects via object identification (Yoon et al., 2002). There is now substantial evidence for this direct route in single-object scenarios (e.g. Bub, Masson, & Cree, 2008; Grèzes, Armony, Rowe, & Passingham, 2003; Grèzes & Decety, 2002; Phillips & Ward, 2002; Riddoch, Edwards, Humphreys, West, & Heafield, 1998; Riddoch, Humphreys, Edwards, Baker, & Willson, 2003; Tucker & Ellis, 1998). These studies reported that, despite being irrelevant to the task, the object affordance facilitates responses consistent with the present object affordance (e.g. Ellis & Tucker, 2000; Phillips & Ward, 2002; Tucker & Ellis, 1998). Extending this line of research, recent studies suggest that not only the action possibilities associated with single objects are extracted in a direct fashion, but also the possibilities of interactions between objects (e.g. Riddoch et al., 2003; Roberts & Humphreys, 2010a, 2010b, 2011a, 2011b; Xu, Humphreys, & Heinke, 2015; Yoon, Humphreys, & Riddoch, 2010). These studies presented images of paired objects which are commonly used together, e.g. a hammer and a nail. In such pairs one object would be the active one (the object being used in the action, e.g. the hammer in a hammer-nail pair) and the other the passive one (requires typically only stabilization during the interaction between objects, e.g. the nail). The spatial relation between the two objects can be further manipulated in a way that the co-location of the objects either indicated a potential interaction between them or not. For instance, a hammer and a nail may imply interaction when the nail is at the appropriate location to be hit by the hammer, but not when the hammer points towards the opposite direction (Figure 1). In a series of studies with such paired objects, Riddoch et al. (2003) reported that patients with extinction improved their ability to identify both objects when the objects were oriented to imply an interaction. For neurologically typical participants Roberts and Humphreys (2011a, 2011b) reported that the "correctly" co-located object pairs facilitated object identification, compared to the "incorrectly" co-located pairs. These results were considered as evidence for the extraction of paired-object affordance, i.e. not only the affordance of single objects, but also the action possibilities between objects were directly perceived, and such direct extraction was further considered as evidence for the processing via the direct route.

However, since most of the existing research used naming or identification task (Riddoch et al., 2003; Roberts & Humphreys, 2010a, 2011a, 2011b; Yoon et al., 2010, though see Roberts & Humphreys, 2010b; Xu et al., 2015; Xu et al., 2017), the identity and the functionality knowledge of the objects were not entirely irrelevant to the task. Therefore, it is possible that the task may have triggered processing in the indirect route. Hence, some of the previously observed effects of implied between-object actions might have been shaped by the object knowledge retrieved during the task, instead of by direct extraction of paired-object affordance. For instance, the affordance of the hammer might have been selected over that of the nail only because the former is recognized as a highly useful tool and knowledge about its usage is retrieved. In this case, an object pair with known functionality or an active object associated strongly with certain functional action would be required for implied between-object actions to affect response selection.

The present study aimed to examine whether it is possible for implied actions in paired-object scenarios to directly affect response selection, when the knowledge of object functionality is absent. Previous studies have demonstrated that the direct route of action retrieval makes contributions to object identification and retrieving action relation between paired objects, as shown by the effect of handedness and the benefit of 1st-person perspective (Humphreys, Wulff, Yoon, & Riddoch, 2010; Yoon et al., 2010). However, since known objects with well-established functionality were used in these studies, the question remains open whether the extraction of between-object action relations is possible without functionality knowledge of objects. In other words, is the indirect routes indispensable for the extraction of action relation? To answer this question, we adopted Xu et al.'s (2015) paradigm in which the explicit task was irrelevant to not only the identity but also the presence of the object pairs, and manipulated the stimuli in order to remove functional association between the object pairs and existing functionality knowledge as much as possible, substantially weakening the involvement of the indirect route. Xu et al (2015) presented the images of task-irrelevant object pairs (e.g. a hammer and a nail) which were followed by imperative central targets. Participants made speeded left/right responses to imperative targets, and the responses were randomly aligned with one of the objects (Figure 1). This design was inspired by the single-object studies discussed earlier, in particular by Phillips and Ward (2002), and the task irrelevance of the objects in these studies is commonly seen as a good operationalization of Gibson's claim of automatic extraction of affordances with little influence from semantic and functional knowledge. In other words, Xu et al.'s (2015) introduced the paradigm commonly used in studying single-object affordance extraction into the processing of paired-object scenarios. In Xu et al. (2015), two effects of implied actions between objects were reported and replicated across experiments: (1) an advantage associated with responses aligned with the active objects (e.g. a hammer in a hammer-nail pair), i.e. when the objects were correctly co-located for between-object actions the responses aligned with the active object were quicker than those aligned with the passive objects (e.g., the nail), and (2) an inhibitory effect on responses aligned with the passive object in the pair, i.e. responses aligned with the passive object were even slower when the pairs of objects were shown in a correct co-location for interaction than when they were not. Note that these effects cannot be easily explained by the presence of atypical object orientation in the incorrect co-location or the Simon effect based on the location of the active objects (Experiment 2 and 3 of Xu et al, 2015).

However, even though there can be little doubt that the effects of implied actions reported in Xu et al. (2015) are based on automatic processing, Xu et al.'s (2015) experiments did not completely rule out the contribution from automatically retrieved knowledge associated with the object pairs. This influence is particularly plausible as the stimuli used in existing studies consist of highly familiar objects frequently seen in everyday life. Therefore, the present paper used the advantage of the active objects and the inhibition on the passive objects reported in Xu et al (2015) as two indexes of the processing of implied between-object actions, and gradually weakened the association between the presented object pairs and established knowledge of object functionality in three experiments. In Experiment 1 the object pairs have no established functionality, e.g. a saw is paired with a bowl. Hence if the effects reported in Xu et al. (2015) can be reproduced without the retrieval of knowledge regarding familiar pairs and their well-learnt functionalities, unfamiliar object pairing would produce effects of implied between-object actions similar to the previously observed effects of implied between-object actions in functionally related object pairs in Xu et al (2015). Experiment 2 examines the potential influence from identity and functionality of "highly usable" objects, i.e. the effects of implied actions might be due to the presence of objects with "high" functional values (e.g. the active objects). Experiment 2 paired objects previously used as passive objects (e.g. a bowl and a screw) and treated the larger one in each pair as an "active" object (e.g. the bowl in the bowl-screw pair). Though these pairs don't include typical active objects, the effects of between-object action relations should remain if the effects can be generated by object co-location and do not rely exclusively on the presence of such objects and the knowledge regarding their functionality. Experiment 3 further replaced the active objects with novel objects without known functionality (novel objects combining action-related structures, i.e. handles, with arbitrary shapes). We reasoned that if the processing of implied actions in paired-object scenarios does not rely exclusively on object knowledge, in Experiment 3 the object pairs without any functional association should still produce the effects of implied between-object actions. Note that with these novel objects, we also test whether action-related structures play an important role in affordance-based processing, as suggest by the dual-route theories.

2 Experiment 1: The effects of implied actions between functionally irrelevant active and passive objects

Experiment 1 examines the role of functionality knowledge of object pairs in extracting implied between-object actions by forming active-passive object pairs which do not have a well-known functionality, e.g. a saw and a bowl. The rationale here is, if the knowledge regarding functionality of paired objects is not critical for the implied action between a given pair of objects to affect response selection, the object pairs formed by functionally irrelevant objects should replicate the effects observed in Xu et al. (2015). As in previous studies using this paradigm (Xu et al., 2015; Xu, Humphreys, Mevorach, & Heinke, 2017), we included two levels of stimulus onset asynchronicity (SOA; 240 ms and 400 ms). On one hand, this factor was introduced to prevent participants from responding rhythmically (Grosjean, Rosenbaum, & Elsinger, 2001). On the other hand, interactions between SOA and the effects of interest would suggest the involvement of the Simon effect, since previous studies reported that the Simon effect decays after a shorter interval of around 200 ms, different from the time course of affordance-based effects which last up to 1200 ms (Hommel, 1994; Phillips & Ward, 2002; Tucker & Ellis, 2001).

2.1 Methods

Twenty-two healthy volunteers (one male, mean age 19 years, range: 18-20 yrs) from the University of Birmingham research participation scheme were recruited. All participants were right-handed and had normal or corrected-to-normal vision. Participants gave informed consent and received course credits for their time. For all three experiments in this study, participants recruitment stopped when the number of sign-ups met a target sample size (twenty four) decided a-priori based on previous studies using similar paradigm (Xu et al., 2017), and would be resumed if valid sample did not meet a low criteria set a-priori at twenty due to no-shows and other unpredictable circumstance. The actual sample size for each experiment was therefore larger than or equal to twenty but smaller than 24 because of no-shows (two for Experiment 1, three for Experiment 2 and four for Experiment 3) and voluntary quitting (one for Experiment 2). Experiment 1 and 2 were approved by the local ethics committee at the University of Birmingham.

The stimuli and the trial sequence were generated using Matlab7 (The MathWorks Inc., Natick, MA, USA) with Psychtoolbox 3. All stimuli were presented on a 17-in Samsung SyncMaster 793s (1280 × 1024 at 75 Hz) connected to a Windows XP computer. The stimuli in Experiment 1 consisted of 23 pairs of line-drawing clip-art style images of objects. Each pair consisted of an active object and a passive object. The two objects were functional irrelevant (See Figure 2A for example stimuli and Supplementary material part A for a complete list of object pairs used in Experiment 1). Some objects appeared in more than one object pair, for instance a glass in the knife-glass pair and the ping-pong bat-glass pair. In total, 16 active objects and 15 passive objects were used as stimuli. On each trial, linedrawings of a pair of objects were presented on the screen. On half of the trials (in the correct co-location condition), the objects were co-located appropriately for interaction. On the other half of the trials (the incorrect co-location condition), the active object was positioned in an orientation inappropriate to interact with the corresponding passive object. In the active-left condition, the active objects were presented on the left side of the screen, while the passive objects appeared on the right side. In the active-right condition, the whole presentation was horizontally flipped from the corresponding active-left presentation. A separate group of 12 participants evaluated the materials (Supplementary material part C), confirming that the objects in each pair are not associated with familiar functional use.

All object images were presented on a light grey background (200, 200, 200, RGB). Each object image subtended 3.2°×3.2° of visual angle. The relative sizes of the objects within each pair matched their relative sizes in real life. The other stimuli included a fixation cross subtending 0.8°×0.8° of visual angle and two response targets (a blue [0, 121, 212 RGB] triangle or a circular disk), both subtended 0.6°×0.6° of visual angle.

The procedure was the same as in Xu et al. (2015). Participants took part individually, with their upper arms resting on the table and the index fingers of both hands resting on the f and the j keys respectively. The experiment consisted of one practice block and five experimental blocks. The practice block consisted of 40 trials, randomly assigned to different conditions. Each experimental block consisted of 128 trials following five warm-up trials. The experimental trials were evenly assigned to different conditions and were presented in a pseudo-randomized order, with no more than three consecutive trials from the same condition. Each warm-up trial was randomly assigned to a condition. Three participants were required to repeat the practice block once because they failed to meet the accuracy criteria (see below) in the first practice block. The accuracy criteria were the same for the practice and the experimental blocks.

At the beginning of each trial, a fixation point was presented at the centre of the screen for 0.4 second. After this the fixation cross disappeared and an object pair appeared. After another 240ms or 400ms (SOA) the response target was presented at the centre of the screen (see Figure 2B). The target and the object pair remained on the screen either until the participants made a response or a period of 1600 ms passed without response. Participants indicated whether the target was a triangle or a circle by using their left or right index finger to press the f or the j key on a QWERTY keyboard. The stimulus–response mapping was counter-balanced across subjects.

The participants were required to respond as quickly and accurately as possible, and they were warned that a block would be repeated either if they missed the target, i.e. if no response were made within the allowed 1600 ms after the target onset, more than three times or if they pressed the wrong key more than three times within that block. Feedback was given immediately after any error.

2.2 Results and Discussion

Participants were highly accurate, with accuracy between 97.1% - 99.3% in different conditions (mean 98.5%, see Table 1). Reaction times (RTs) of the correct responses were initially trimmed to remove those shorter than 100 ms. RTs out of 2.5 standard deviations of each participant were then discarded in a non-recursive manner for each participant. Discarded trials were 3% of total trials (ranged 1.4% - 3.7% for individual participants). The same procedure for outlier removal was applied in all experiments.

Mean RTs were calculated for each participant in each condition, and were entered into an ANOVA with SOA (240 ms and 400 ms), co-location (correct vs. incorrect), layout of objects (active objects on the left side vs. on the right side) and response compatibility (congruent with active objects vs. with passive objects) as within-subject factors. There was a main effect of SOA, $F(1, 21) = 123.70$, $p < .001$, $\eta^2 = 0.86$, with RTs in the 240 ms SOA condition being longer than in the 400 ms SOA condition (MD = 24 ms). The main effect of response compatibility was significant, $F(1, 21) = 6.53$, $p = .018$, $\eta^2 = 0.24$, with the responses congruent with the active objects being quicker than those congruent with the passive objects (MD = 4 ms). There was a significant interaction between co-location and response compatibility, $F(1, 21) = 20.76$, $p <.001$, $\eta^2 = 0.50$, see Figure 3. No other interaction was significant. The analysis of simple effects revealed that in the correct co-location condition, compared to the incorrect co-location condition, the responses congruent with the passive objects were slower ($p = .033$, MD = 6 ms, $\eta^2 = 0.20$), but those congruent with the active objects were quicker ($p = .003$, MD = 7 ms, $\eta^2 = 0.30$). In addition, the analysis of the other effect of interest, the advantage of the active objects in the correct co-location condition, showed that the responses congruent with the active objects were quicker than the passive objects in the correct co-location condition ($p < .001$, MD = 11 ms, $\eta^2 = 0.49$, see Figure 3).

The results replicated the critical effects of implied between-object actions reported in Xu et al. (2015), i.e. the advantage of the active objects in the correct co-location condition and the inhibition on the passive objects in the correct compared to the incorrect co-location condition. These findings suggest that an established functionality of the object pairs is not a prerequisite for the effects of implied between-object actions.

3 Experiment 2: The effects of implied action between passive objects

Experiment 1 demonstrated that when the objects were presented in the object pairs which do not have established functionality, the interactions implied by their co-locations still produced two effects similar to those produced by object pairs with well-learnt functionality. Experiment 2 intends to further examine whether the presence of some particular objects strongly associated with certain functional action, i.e. the active objects, evoked these effects. Experiment 2 paired the objects previously used as passive objects (e.g. a bowl and a screw) and treated the larger one in each pair as the "active" object (see Figure 4 for examples). The arbitrary assignment of "active" objects were to maintain perceptual similarity with the functionally related object pairs used in previous studies, in which the active objects were typically larger (Xu et al., 2015; Xu et al., 2017). In the "correct co-location" condition, the objects were positioned so that their orientation and their relative location were similar to how they were in the correct co-location condition of previous experiments. Hence, in terms of orientation and relative location, both objects have potential to be engaged in certain between-object actions. The orientation of the "active" objects in each pair was manipulated in the incorrect co-location condition.

3.1 Methods

A new sample of twenty healthy volunteers (two males, mean age 19 years, range: 18-23 yrs) from the University of Birmingham research participation scheme was recruited. All participants were right-handed and had normal or corrected-to-normal vision. Participants gave informed consent and received course credit for their time.

The procedure was the same as Experiment 1 except for the stimuli. The stimuli in Experiment 2 consisted of 25 pairs of line-drawing clip-art style images of objects. Each pair consisted of one "active" and one passive object, both having been used as passive objects in previous studies (Experiment 1 and Xu et al., 2015). The two objects were functionally irrelevant (see Figure 4 for the example stimuli and Supplementary material part B for a complete list of object pairs used in Experiment 2). Some objects appeared in more than one object pair, for instance a screw as a passive object in the glass-screw pair and the pan-screw pair. In total, five "active" objects and five passive objects were used as stimuli. Material evaluation by a separate group of volunteers confirmed that the objects in each pair are not typically used together (see Supplementary material part C).

3.2 Results

Same as Experiment 1, reaction times (RTs) of the correct responses were initially trimmed to remove those shorter than 100 ms. RTs out of 2.5 standard deviations of each participant were then discarded in a non-recursive manner for each participant. Discarded trials were 2.6% of total trials (ranged 1.4% - 4.0% for individual participants). Participants were highly accurate, with accuracy between 96.5.2% - 99.3% in different conditions (mean 98.5%, see Table 2).

To examine whether Experiment 2 replicated the effects of implied actions within object pairs with established functionality, mean RTs of each participant were entered into an ANOVA with SOA (240 ms and 400 ms), co-location ("correct" vs. incorrect), the layout of objects (the "active" objects on the left side vs. on the right side) and response compatibility (aligned with the "active" object vs. the passive object) as within-subjects factors.

There was a main effect of SOA, $F(1, 19) = 82.16$, $p < .001$, $\eta^2 = 0.81$, with RTs in the 240 ms SOA condition being longer than in the 400 ms SOA condition (MD = 18 ms). There was a significant interaction between co-location and response compatibility, $F(1, 19) = 10.14$, $p = .005$, $\eta^2 = 0.35$, and an interaction between SOA, response compatibility and co-location, $F(1, 19) = 8.38$, $p = .009$, $\eta^2 = 0.31$. The analysis of the simple effects suggested that in the 240 ms SOA condition, the response aligned with the passive objects were marginally quicker in the incorrect co-location condition than in the "correct co-location" condition ($p = .058$, MD = 5 ms, $\eta^2 = 0.18$), but this did not apply to those aligned with the active objects ($F < 1$). In the 400 ms SOA condition, this effect reached significance for the responses aligned with the passive objects ($p = .016$, MD = 12 ms, $\eta^2 = 0.27$) but not those aligned with the active objects (*F* < 1). Analysis of the other effect of interest, the advantage of the active objects in the "correct co-location" condition revealed that, in the 240 ms, but not the 400 ms ($p > 0.1$), SOA condition, when the co-location was "correct", responses aligned with the "active" objects were quicker than those aligned with the passive objects ($p = .040$, MD = 7 ms, $\eta^2 = 0.20$). Since the two effects of interest became modulated by SOA and were not significant in all SOA levels, without further differentiating the "active" objects (according to whether it has a handle, see below), we did not fully replicate previously reported effects of implied between-object actions (the advantage of the active objects in the "correct co-location" condition and the inhibitory effect of co-location on the passive objects).

However, further inspection revealed that the "active" objects used in Experiment 2 can be separated into two groups. For some objects, the grasping/manipulation required in their functional use is primarily afforded by a salient action-related structure, e.g. a handle of a cup. For objects without handle, the manipulation requires grasping at the main body of the objects, e.g. a bowl. Action-related structures have been reported playing important roles in object perception and affordance extraction in single-object scenarios (e.g. Buccino et al., 2009; Cho & Proctor, 2011; Matheson, Newman, Satel, & McMullen, 2014; Vainio et al., 2014) as well as paired-object scenarios (Wulff & Humphreys, 2015). Taking these findings into account, it is natural to ask whether it is possible that in the object pairs with distinct action-related structures (handles), an impact of between-object affordance is still observable. Consequently, in the following analysis, as an exploration, we compared responses to the "active" objects with and without handle. In such a contrast we asked whether, instead of the functionality of the active objects, it is the action-related object structures that produced the effects of implied between-object actions observed in Xu et al. (2015).

Handle vs. handle-less

To examine the role of the action-related structures in producing the effects of implied between-object actions, RT data of correct responses were entered into an ANOVA with an additional within-subject factor, the handle of the “active” object (the “active” object in the object pair has a handle vs. does not have a handle). Fifteen of the 25 pairs of objects falls into the with-handle category and the rest the without-handle category.

There was a main effect of SOA, $F(1, 19) = 78.45$, $p < .001$, $\eta^2 = 0.81$, with RTs in the 240 ms SOA condition being longer than in the 400 ms SOA condition (MD = 17 ms). There was a significant interaction between co-location and handle, $F(1, 19) = 12.88$, $p = .002$, $\eta^2 = 0.40$, an interaction between response compatibility and handle, $F(1, 19) = 7.86$, $p = .011$, $\eta^2 = 0.29$, and an interaction between co-location and response compatibility, $F(1, 19) = 8.75$, $p = .008$, $\eta^2 = 0.32$. Above all, the three-way interaction between handle, co-location and response compatibility was significant, $F(1, 19) = 5.24$, $p = .034$, $\eta^2 = 0.22$ (see Figure 5). The analysis of simple effects suggested that for the pairs with a handle on the “active” objects, the responses aligned with the passive objects were quicker in the incorrect co-location condition than in the “correct co-location” condition ($p = .001$, MD = 17 ms, $\eta^2 = 0.43$), but this effect did not exist for the object pairs when the “active” objects did not possess handles ($p > 0.2$), and were not significant for responses aligned with the active objects in either kind of object pairs (*p*s > 0.1). Analysis of the other effect of interest, the advantage of the active objects, further revealed that when the “active” objects have handles, the responses aligned with the passive objects were slower than those aligned with the “active” objects in the “correct co-location” condition ($p = .003$, MD = 14 ms, $\eta^2 = 0.37$), but this effect did not exist for the object pairs when the “active” objects did not possess handles ($p > 0.1$). In other words, the effects of implied between-object actions were replicated in “with-handle” pairs, but not in the “without handle” pairs.

In addition, there was an interaction between handle and response compatibility, $F(1, 19) = 7.86$, $p = .011$, $\eta^2 = 0.29$, and between handle-ness, SOA and response compatibility, $F(1, 19) = 4.98$, $p = .038$, $\eta^2 = 0.21$ (see Figure 6). Analysis of simple effect revealed that in 240 ms SOA condition, responses aligned with “active” objects with a handle were quicker than those aligned with the passive objects ($p = .002$, MD = 11 ms, $\eta^2 = 0.42$). The same effect was not significant when the “active” object in a pair does not have a handle ($p > 0.2$), or in 400 ms SOA condition ($F < 1$). Note here this interaction reflected influences independent from the co-location between objects. This interaction might reflect a bottom-up response bias towards the salient handle regardless of object orientation. There was also the significant interaction between SOA, co-location and response compatibility, but not involving handle-ness, as reported in the first set of ANOVA.

3.3 Discussion

Without considering whether the “active” objects have a handle, the results only partially replicated the results of Experiment 1. The inhibitory effect on the passive objects reduced to marginally significant in the 240 ms SOA condition, and the advantage for the active objects ceased to be significant in the 400 ms SOA condition. These changes suggest that the effects were not as clear-cut as in Experiment 1 or other previous experiments using active-passive object pairs (Xu et al., 2015). However, when trials presenting the “active” objects with a handle were analyzed separately from those without handles, the results showed a clear replication of our earlier findings. Note that the influence of handles was observed when the two objects in each pair do not afford well-known between-object actions. The effects of implied between-object actions persisted in object pairs as long as the “active” objects have an action-related structure. Such findings are consistent with previous report that action-related structures play important roles in affordance extraction (e.g. Buccino et al., 2009;

Wulff & Humphreys, 2015). This suggested that the presence of typical active objects (most of them are tools and the active manipulation of these objects are more likely to be associated with established functionality comparing to the passive objects) was not an exclusive prerequisite for the effects of implied actions between objects. This result indicates that the effects of implied actions between objects on response selection exist without the retrieval of the functionality knowledge of the active objects. However, the factor “handleness” was only included in a post-hoc manner in this experiment, based on a limited set of stimuli. Therefore, its effect should be interpreted with caution. Experiment 2 raised the possibility that “handleness” plays a role, and this possibility was further examined in Experiment 3. Experiment 3 asked whether the action-related structures, i.e. the handles of objects in our stimuli, produce the effects of between-object action relations when functional knowledge is lacking.

4 Experiment 3: The effects of implied action with novel objects

Experiment 2 pointed to the possibility that action-related structures of the objects might play a key role in generating the effects of implied between-object actions. If this is true, any object with a handle, when they were paired with a passive object, should produce these effects. Experiment 3 tested this possibility by replacing the active objects with novel objects. The novel objects were constructed by taking handles from previously used active objects and joint them with arbitrarily shaped blocks (see Methods and Supplementary material part D for details). The novel objects were then paired with without-handle passive objects previously used in this paradigm (Xu et al., 2015). The task was the same as in Experiment 1 and 2. This change in materials should diminish or alter the effects in question if action-related structures such as handles were not sufficient to affect response selection in the paired-object scenarios.

4.1 Methods

Twenty healthy volunteers (eight males, mean age 23 years, range: 18-27 yrs) from Beijing Normal University were recruited for Experiment 3. All participants were right-handed and had normal or corrected-to-normal vision. Participants gave informed consent and received money for their time. The experimental protocol was approved by the Institutional Review Board of Beijing Normal University.

The procedure of Experiment 3 was the same as Experiment 1 and 2 except for the stimuli. The stimuli consisted of 80 pairs of line-drawing style images of objects. Each pair consisted of one active object and one passive object. Each active object was constructed specially for this experiment by combining an arbitrary shape and a handle structure from a familiar object previously used in the present paradigm (Experiment 1 or Xu et al., 2015). Specifically, four kinds of handles were used. They were taken from a spoon, a spatula, a saucepan and a kettle. Five arbitrary shapes were used, combining with each of the handles, resulting in 20 novel active objects (see Supplementary material part D). These twenty active objects were paired with each of four passive objects (the nail, the bowl, the tennis ball and the nut). They were chosen from the passive objects used in Xu et al. (2015), and none of them has a handle. The arbitrary shapes and the passive objects were chosen so that their appearance does not resemble any action-related object pairs commonly seen in daily life (see Figure 7 for example stimuli and Supplementary material part D for a complete list of object pairs used in Experiment 3). This was confirmed in the evaluation of the materials by a separate sample of 12 participants (see Supplementary material part C). As in Experiment 1 and 2, the correctness of object co-location referred to whether the co-location implies an interaction between objects or not. As in Experiment 1 and 2, the correctness was manipulated by the orientation of the active objects. Object pairs were assumed to imply an interaction when the handles were on the side of the arbitrary shape opposite to the passive objects, appearing to direct the arbitrary shape towards the passive objects. Otherwise, the co-location was considered "incorrect" for between-object interaction. Note that such associations between the handle location and the correctness of co-location is common in real object pairs, such as a screwdriver and a screw or a spoon and a bowl. Also note that the material evaluation reported in Supplementary material part C verified this manipulation, as a separate sample of participants rated the object pairs used in Experiment 3 are more appropriate for interaction in our "correct" co-location condition than in the "incorrect" co-location condition.

4.2 Results

Same as Experiment 1 and 2, reaction times (RTs) of the correct responses were initially trimmed to remove those shorter than 100 ms. RTs out of 2.5 standard deviations of each participant were then discarded in a non-recursive manner for each participant. Discarded trials were 2.3% of total trials (ranged 0.9% - 3.5% for each participant). Participants were highly accurate, 98.0% - 99.6% across conditions (mean 99.1%, see Table 3).

To examine whether the overall RTs pattern replicated our earlier findings, mean RTs of each participant were entered into an ANOVA with SOA (240 ms and 400 ms), co-location (correct vs. incorrect), layout of objects (the active objects on the left side vs. on the right side) and response compatibility (aligned with the novel active object vs. the passive object) as within-subject factors.

There was a main effect of SOA, $F(1, 19) = 72.47$, $p < .001$, $\eta^2 = 0.79$, with RTs in the 240 ms SOA condition being longer than in the 400 ms SOA condition (MD = 19 ms), a main effect of co-location, $F(1, 19) = 38.98$, $p < .001$, $\eta^2 = 0.67$, with RTs in the correct co-location condition being longer than in the incorrect co-location condition (MD = 7 ms), and a main effect of response compatibility, $F(1, 19) = 18.02$, $p < .001$, $\eta^2 = 0.49$, with RTs aligned with the active objects being shorter than those aligned with the passive objects (MD = 7 ms). There was an interaction between SOA and co-location, $F(1, 19) = 7.77$, $p = .012$, $\eta^2 = 0.29$ (Figure 8). Simple effect analysis revealed that the difference between the correct and the incorrect co-locations was larger in the 240 ms SOA condition (MD = 9 ms, $p < 0.001$, $\eta^2 = 0.60$), comparing to the 400 ms SOA condition (MD = 3.81, $p = 0.005$, $\eta^2 = 0.35$). Importantly, there was a significant interaction between co-location and response compatibility, $F(1, 19) = 50.53$, $p <.001$, $\eta^2 = 0.73$. The analysis of the simple effects suggested that the responses aligned with the passive objects were quicker in the incorrect co-location condition than in the correct co-location condition ($p <0.001$, MD = 16 ms, $\eta^2 = 0.80$), but co-location did not affect the responses aligned with the active objects ($p = 0.22$). The analysis of the other effect of interest, the advantage of the active objects in the correct co-location condition, further revealed that the responses aligned with the novel active objects were quicker than those aligned with the passive objects in the correct co-location condition ($p < .001$, MD = 16 ms, $\eta^2 = 0.73$). There was no other significant main effect or interaction.

4.3 Discussion

The results replicated the results of functionally irrelevant object pairs in Experiment 1 and those of the object pairs with handles in Experiment 2, as well as that of the object pairs with established functionality in Xu et al. (2015). Note that the active objects used in Experiment 3 were completely novel to the participants, and did not bear any functionality or identity. As in Experiment 1 and 2, there was no set functionality that can be realized by the presented object pairs, and, one step further than Experiment 2, even the potential functionality of the active objects themselves was ambiguous, since the handles were added to arbitrary shapes without apparent cue of utility. The only implication of actions between objects was the relative location of the orientation of the handle of the active object and the passive object. The results of Experiment 3 tested the hypothesis raised in Experiment 2 and showed that in paired-object scenarios, the relative location of the handle of the objects, as an action-related feature, is probably sufficient to produce response selection effects similar to that of implied actions between objects with established functionality (Xu et al., 2015). This suggests that in the circumstance when the object identity and the knowledge of their functionality was absent, the possibility of interaction defined by the co-location and the action-related structure of objects may still allow the extraction of implied action relation between objects and affect response selection .

Note that the passive objects in Experiment 3 were known objects. Thus, the automatic extraction of semantic information regarding the passive objects may still exist in Experiment 3. However, we consider this factor unlikely to be responsible for the effects of interest. First of all, semantic knowledge of the passive objects cannot generate the effects in question alone. The semantic information from the passive objects remained the same across co-location conditions in Experiment 3 (the same known passive objects, hence the same semantic knowledge). Therefore the difference between co-location conditions, in particular the inhibition of the passive objects, could not have remained if it relies solely on the semantic knowledge of the passive objects. Further, the effects are unlikely to come from the joint impact of semantic knowledge of the passive objects and the spatial location between this object and an action-related structure, e.g. a handle, of the other object. In Experiment 2 of Xu et al. (2015), the passive objects (known objects), instead of the active objects, changed orientation in the incorrect co-location condition. With this manipulation, the effects of implied between-object actions vanished, suggesting that the joint impact of the presence of semantic knowledge of the passive objects and the manipulation of co-location (both true for that experiment) cannot be the cause of the effects in question. Instead, this pointed to a possibility that the active objects play a leading role in the perception of implied between-object actions. This possibility is further supported by a TMS study (Xu et al, 2017). It reported that the effects of implied between-object actions diminished only when TMS interfered with aIPS contralateral to the active objects, which, considering the contralateral dominance of aIPS in affordance-related processes, suggests that the processing of the active objects, instead of the passive objects, is critical in generating the effects of implied between object actions. However, we agree that the exact contribution of the passive objects in the perception of implied between-object actions merits further investigation. Future work is needed to directly examine the exact contribution of the passive objects in generating effects specific to paired object scenarios, probably by directly manipulating the functional familiarity of the passive objects.

5 General Discussion

Previous studies have demonstrated that implied actions between objects affect responses even though the implied actions are task-irrelevant (e.g. Riddoch et al., 2003) or both the actions and the objects are task-irrelevant (Xu et al., 2015). These effects were interpreted as evidence that humans not only automatically process action possibilities offered by single objects but also the actions implied by object pairs. The present paper examined the directness of such extraction, i.e. whether such effects of implied between-object actions depend on the retrieval of object knowledge. To do so, in three experiments, the present study gradually weakened the association between object pairs and any specific functionality. With such manipulation, the results of the present study still replicated the effects of implied between-object actions with established functionality (Xu et al, 2015), suggesting that the effects of implied between-object actions may remain without functionally typical object pairing (Experiment 1) and the presence of objects with high functional values (Experiment

2). Instead, the crucial factor seems to be the action-related structures of objects (Experiment 2 and 3)[1]. In addition, we did not find evidence that the effects of interest declined with SOA, consistent with the same null results reported in our previous studies using familiar objects (Xu et al., 2015; Xu et al., 2017). This does not agree with the time course of the Simon effect, which typically reduced rapidly at around 200 ms (Hommel, 1994; Phillips & Ward, 2002; Tucker & Ellis, 2001). Hence, the maintenance of the effects of interest after 400ms suggests that the Simon effect is unlikely to be the sole source of our findings. Note that this lack of an SOA effect does not exclude the possibility of the Simon effect contributing to the observed effects of implied between-object actions. Also, given previous reports of the Simon effect longer than 200 ms (e.g. Symes, Ellis, & Tucker, 2005), strong conclusion cannot be drawn on this issue without systematically manipulating SOA in a wider time window.

These results empirically illustrated the directness and automaticity of the extraction of action-relation information in paired-object scenarios. Collectively with Xu et al.'s (2015), the results extended existing research which demonstrated the automatic extraction of action-related information in single-object scenarios, and suggested that action possibilities between objects could also be automatically and directly extracted from visual scenes, resembling the directness Gibson suggested for affordance extraction. Some specific points are discussed in details in the following sections.

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[1] In the light of recent discussions concerning effect size inflation and *p*-hacking (e.g. Wicherts et al., 2016) we conducted a post-hoc power analysis for the two contrasts of interest (the advantage of the active objects in the correct co-location condition and the inhibition of the passive objects) based on the average effect size of these two effects across all three experiments (including the insignificant ones). We found that the present study had a power of 0.80 and 0.83 for the two effects respectively. Also it is worth noting that we have now replicated these two effects across three studies (see also Xu et al., 2015; Xu et al., 2017).

5.1 The impact of the action-related object structures in paired-object scenarios

The involvement of the direct route and the impact of action-related structures has been demonstrated in object perception as well as affordance extraction in the single-object scenarios (e.g. Buccino et al., 2009; Matheson et al., 2014). In the paired-object scenarios, the potential for action-related structures to affect perception has been demonstrated in a study with patients with visual extinction in which handles affected attention distribution in paired-object scenarios with familiar objects (Wulff & Humphreys, 2015). Advancing this line of research, the present study empirically illustrated that action-related structures in the paired-object scenarios are sufficient to affect the extraction of potential interaction on the between-object level, not having to rely on object knowledge. Note that Xu et al. (2015) has demonstrated that the two effects of implied between-object actions cannot be simply attributed to the effect of single-object affordance. For instance, Experiment 3 in Xu et al. (2015) reported that the effects of implied between-object actions did not occur in the single-object displays with the active objects presented alone but in the same location and orientation as in the paired-object scenarios, suggesting that the effects of implied between-object actions were only evident in the paired-object scenarios. By demonstrating the influence of the action-related structures on the effects of implied between-object actions, the present study suggests that action-related features might be a key feature of objects in not only the single-object scenarios (e.g. Buccino et al., 2009; Matheson et al., 2014), but also the perception of action relations between paired objects. This is also consistent with the reported impact of handles in familiar paired-object scenarios in perceptual report task (Wulff & Humphreys, 2015).

The reliance on the action-related structures revealed in Experiment 2 and 3 is consistent with the dominance of the active objects in the paired-object affordance effect (Xu et al., 2015; Xu et al., 2017). The active objects according to our definition are the ones affording the major actions in object pairs, while the presence of action-related structure might be a signal of the inherent “activeness” of the objects. Consequently, in Experiment 2 and 3, comparing with those without handles, the objects with a handle might make stronger implication of interactions with the other object in the pair and were therefore favoured in response selection.

The impact of action-related object structures in the perception of implied between-object actions highlights the involuntariness and the directness of the extraction of implied between-object actions in the paired-object scenarios. In fact, the implied actions between objects were shown to be extracted in a way resembling the extraction of single-object affordances, not necessarily dependent on the knowledge of objects and object pairs. This evidence suggests that besides the specific, object-based affordance extracted in a local manner, between-object information might also be part of the primary information picked up from multi-object scenarios. This speculation differs from existing theoretical suggestions which attribute the detection of single-object affordance to task context, intention and end-goal of manipulation (e.g. Binkofski & Buxbaum, 2013; Borghi & Riggio, 2009, 2015; Cisek, 2007; Sartori, Straulino, & Castiello, 2011; Thill, Caligiore, Borghi, Ziemke, & Baldassarre, 2013; Valyear, Chapman, Gallivan, Mark, & Culham, 2011) in that it adds the extraction of between-object spatial information into the list of factors contributing to affordance selection. Future work is needed to directly test this proposal, probably by examining the neural correlates of the proposed extraction of interaction possibilities in multiple-object scenarios, and comparing it with that of affordance extraction in the single-object scenarios.

Note that we do not claim that the between-object action relations were necessarily extracted as a form of (Gibbsonian) affordance. Instead, we acknowledge that the Simon effect may also contribute to the perception of action relations between objects, as some researchers suggested for the affordance-related effects in the single-object scenario (e.g. Cho & Proctor, 2010, 2011). For instance, it is possible that the responses congruent with the passive objects in the correct co-location condition were slowed down in Experiment 2 and 3 because of the combined impact of an affordance-orientation effect and a Simon effect based on the location of the active objects or their handles, while in the incorrect co-location condition, these responses were no longer affected by the affordance-orientation effect due to the change of orientation of the active object, hence the inhibition on the passive objects in the correct co-location condition. One possibility to address this issue is to choose active objects the action-related structure of which was not on the opposite side of the passive objects in interaction, such as a watercan with a top handle or a pot with bi-lateral handles, and examine whether the effects of implied between-object actions would diminish with such stimuli. Note that such a combined impact of affordance-orientation effect and the Simon effect does not conflict with the conclusion of the present study, and may well be the mechanism behind the automatic responses to unknown implied between-object actions, as observed in the present study. Future studies need to test this possibility directly. However, attributing the effects to affordance or not, the results reported here highlighted the directness of the perception of action relation between objects.

Finally, in the single-object scenarios, object structures have been suggested to aid actions more complex and controlled than reaching or grasping, such as tool use. For instance, a recent theory of tool use, the Four Constraints Theory (Osiurak, 2014), discussed the involvement of affordance in human tool use. It suggests that tool use requires "technical" reasoning based on mechanical knowledge representing the physical laws of object interactions, e.g. lever principle, causality, etc. Moreover, it postulates that single object affordance and technical reasoning work together in a dialectical way, and affordance perception supports translation of the abstract outcome of technical reasoning into concrete interactions with the environment. Here we suggest that in addition to single object affordances, the “interaction possibility”, i.e. the possibility of between-object actions defined by object co-location and the relative location of action-related structures, might support the translation of reasoning into concrete interactions. Admittedly, the task of the present study was designed to avoid more complex cognitive processes such as the retrieval of object knowledge and the reasoning process dictated by the presence of various constrains, therefore cannot cover the entire process of dialectic interaction between perception of between-object action relations and mechanical reasoning. Future work is needed to directly examine the relation between the automatic extraction of structure-based interaction possibilities and the tool use reasoning in tasks involving more intentional object manipulation.

5.2 The impact of object knowledge

The findings of the present study suggest that the knowledge of object pairs is not an exclusive prerequisite for the extraction of paired-object affordance. Similarly, a study with a Balint patient found that in an object identification task, action relation between objects facilitated perceptual report of objects (illustrated in the contrast between the correct and the incorrect co-location conditions), and this effect was not reduced by less familiarly paired objects affording feasible actions but lower familiarity (Humphreys, Riddoch, & Fortt, 2006). Moreover, in a functional magnetic resonance imaging (fMRI) study, Roberts and Humphreys (2010a) found that the activation of bilateral lateral occipital complex (LOC) was increased in the correct co-location compared to the incorrect co-location condition, and this effect exists regardless of the familiarity of the pair. These results, together with the results of the present study, suggest that implied between-object actions may affect responses without well-established functionality knowledge of the object pairs.

However, some previous studies did report the influence from the functionality of objects. For instance, Green and Hummel (2006) found that the correct co-location for interaction facilitated object identification, but this effect existed only when the two objects belonged to the same functional group (equivalent to familiar pairs in Xu et al., 2015), but not when they were functionally irrelevant (similar to the unfamiliar pairs in Experiment 1). In addition, Riddoch et al., (2003) found that in patients with extinction, identification was facilitated by the correct co-location when the presented objects were normally used together (e.g. a bottle and a glass), but not when the object pairings were not typical (a bottle and a bucket) or random (a bottle and a ball). In healthy adults, Bach, Knoblich, Gunter, Friederici, and Prinz (2005) reported mutual influence between functional and action-related spatial judgement, and these two kinds of judgement interact in affecting neural activation along the intraparietal sulcus (Bach, Peelen, & Tipper, 2010). These findings suggested the contribution of a knowledge-mediated route in the perception of action relation between objects, and suggested that this route may work in parallel with the direct route responding to the spatial features of action relation. We attribute the difference between our finding and the results of these studies to the difference in the experimental tasks. An object identification task might lead to an involuntary retrieval of the semantic knowledge of the object pairing, which might affect the responses accordingly. For instance, the performance with correctly co-located objects with strong functionality would have improved compared to the responses to object pairs where these associations are not available. The fact that the present study used a semantic-free task and did not find evidence supporting the involvement of object knowledge in response selection based on between-object actions suggests that such effects of functionality might only become apparent given matching task requirement and attention status (e.g. McNair & Harris, 2016). However, note that the findings of the present study does not go against paralleled functioning of the direct and the knowledge-based routes in perceiving action relations (Bach et al., 2005; Bach et al., 2010; Riddoch et al., 2003). The present study endeavored to reduce the involvement of the knowledge-based route to test the possibility of extracting between-object action relations solely via the direct route. Thus, it was not designed to capture interaction between the two routes. Future work is required to further explore the impact of object identity and knowledge as well as the condition of their interaction with the direct route.

6 Conclusion

Taken together, the present paper revealed that, retrieving the identity and functional knowledge of objects is not an exclusive prerequisite of the perception of action relations between objects. It is possible to perceive affordances between objects by processing action-related structures across paired-object scenarios directly, when semantic knowledge was absent.

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Captions

Table 1: Average accuracy and reaction times (RTs) of each condition in Experiment 1

Table 2: Average accuracy and reaction times (RTs) of each condition in Experiment 2

Table 3: Average accuracy and reaction times (RTs) of each condition in Experiment 3

Figure 1. Illustration of the main conditions in Xu et al., 2015

Figure 2. A. Example stimuli and the main conditions of Experiment 1. B. The procedure of Experiment 1. The participants were required to make speeded key-press responses according to the shape of the central target (in display 2). The target can be either a triangle or a circle, and half of the participants were instructed to press key f with the left index finger in response to a triangle and to press key j with the right index finger in response to the circle, and the rest participants were instructed to respond according to reversed stimuli-response mapping. The responses made by the hand on the same side with the active objects (right hand response in this figure) were considered congruent with the affordance of the active objects and the responses on the other side (left hand response in this figure) congruent with the affordance of the passive objects.

Figure 3. *The results of Experiment 1.* The correct co-location slowed down responses congruent with the passive object (shown by the two bars on the left). The responses congruent with the active objects were quicker than those congruent with the passive objects when the co-location was correct (shown by the two dark bars). The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of the contrasts of interest is denoted on the figure (a = .05).

Figure 4. Example stimuli and the main conditions of Experiment 2.

Figure 5. *The three-way interaction between the presence of a handle, co-location and response compatibility* in Experiment 2. The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of the contrasts of interest is denoted on the figure (a = .05).

Figure 6. *The three-way interaction between SOA, the presence of handle and response compatibility* in Experiment 2. The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of the contrasts of interest is denoted on the figure (a = .05).

Figure 7. Example stimuli and the main conditions of Experiment 3.

Figure 8. *The results of Experiment 3.* The correct co-location slowed down responses congruent with the passive object (shown by the two bars on the left). Responses congruent with the active objects were quicker than those congruent with the passive objects when the co-location was correct (shown by the two dark bars). The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of the contrasts of interest is denoted on the figure (a = .05).